Science and technology prospects for ultra-cold atoms

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- Atom de Broglie wave sensors
- S&T impact
- BEC impact
- Correlated atom systems

Atom de Broglie wave sensors

Position information

Problem: How obtain precise position information without GPS?

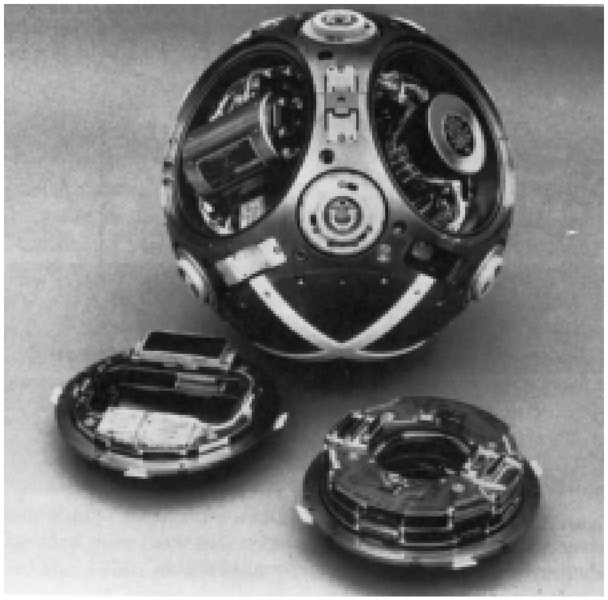
Next generation Inertial Navigation System (INS) solution: Improved INS may enable accurate global positioning without external reference signals

Current INS limitations:

- gyroscope drift (angle random walk)
- gravity compensation
- system cost and complexity

Atom de Broglie-wave interference sensors address these current limitations

Existing high-accuracy technology



19,000 parts

$300K/accelerometer in '89

1970 technology. 2001, 652 units ordered.

Source: www.fas.org

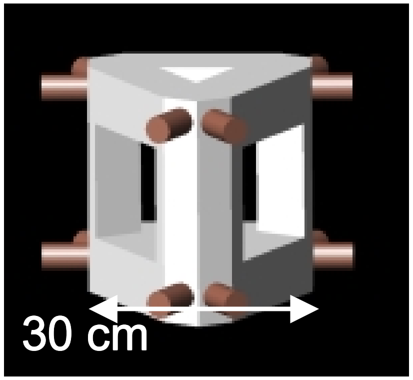
Existing systems:

- Triad of gyroscopes (mechanical)
- Triad of accelerometers
- Precision gimbal mounts

Gravity assisted-navigation with atom interferometric (AI) sensors

AI acceleration sensors offer breakthrough bias-stability and scale-factor stability

- **enables high accuracy gravity gradiometry**
- **enables all-accelerometer-based gravity compensated navigation**
- **3 year transition to field-tested systems. Leverage NIMA and Navy investments.**



Conept design for gravity compensated IMU

Concept design for 2.75”x1.75”, 10^{-8} g/Hz$^{1/2}$ 2-axis accelerometer

Cut-away view illustrating core sensor component: a Cs vapor cell. Not shown: control electronics.

AI sensor applications

Gravity compensated navigation
- Map-matching
- Real-time gravity anomaly correction for INS

Gravity anomaly characterization
- Underground facility detection

Strategic platforms
- Precision munitions
- Submarine/surface ship
- Land vehicles
- Helicopter/fixed wing aircraft
- ULDB Balloon flight
- Satellite constellation

Commercial/civilian applications
- Satellite geodesy
  - Earthquake prediction
  - Water table monitoring
- Oil/mineral exploration

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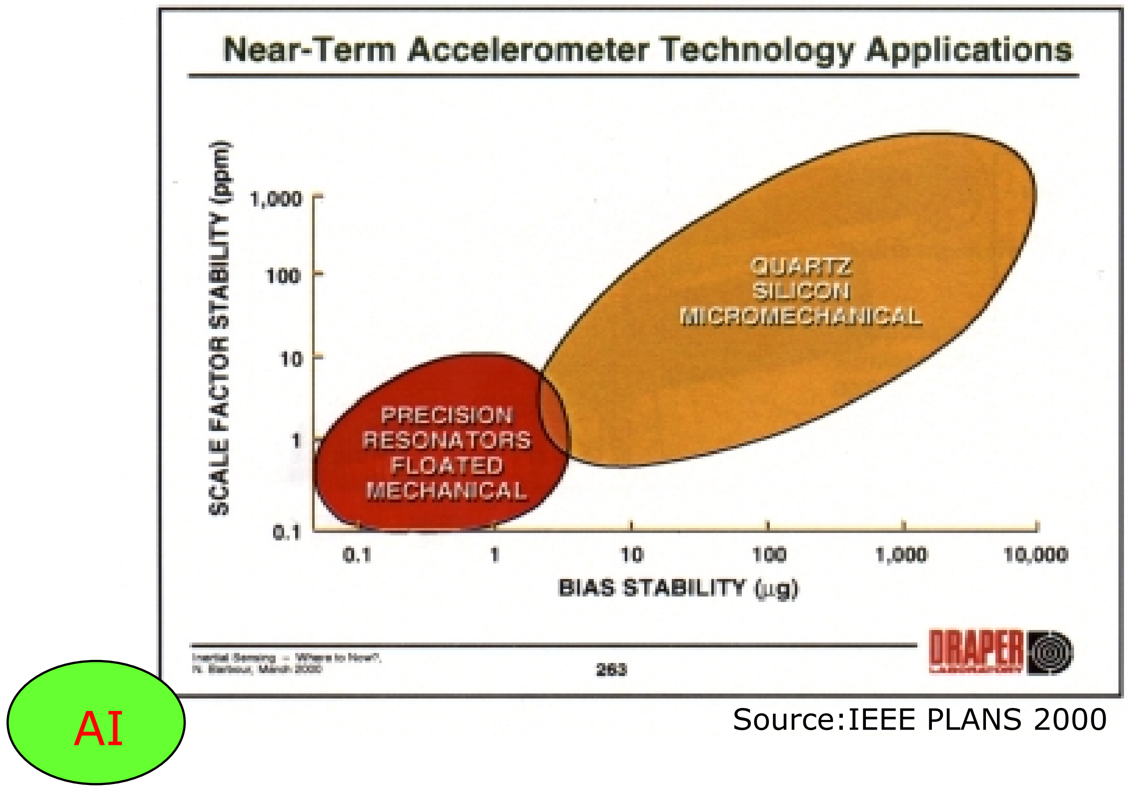
Core sensor technology: High accuracy accelerometers

Light-pulse AI accelerometers:

Scale Factor stability: 10^{-12}

Bias stability: $<10^{-10}$ g



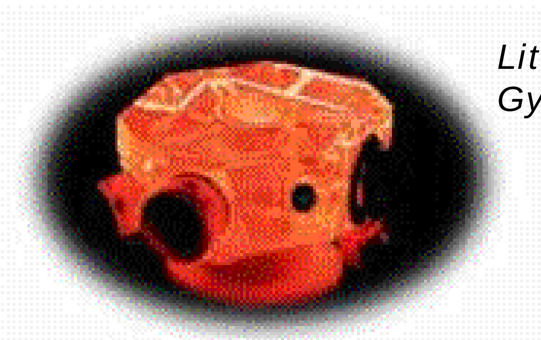
Source:IEEE PLANS 2000

1000x improvement over state-of-the-art in these key sensor parameters.

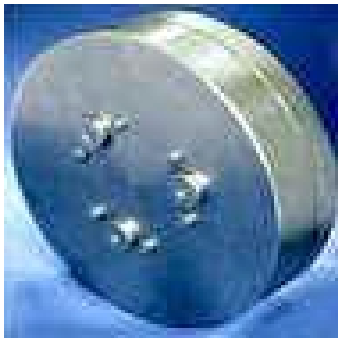
Laboratory realizations at Stanford and Yale.

Interferometric sensors

Optical Interferometry



Litton Ring Laser Gyroscope

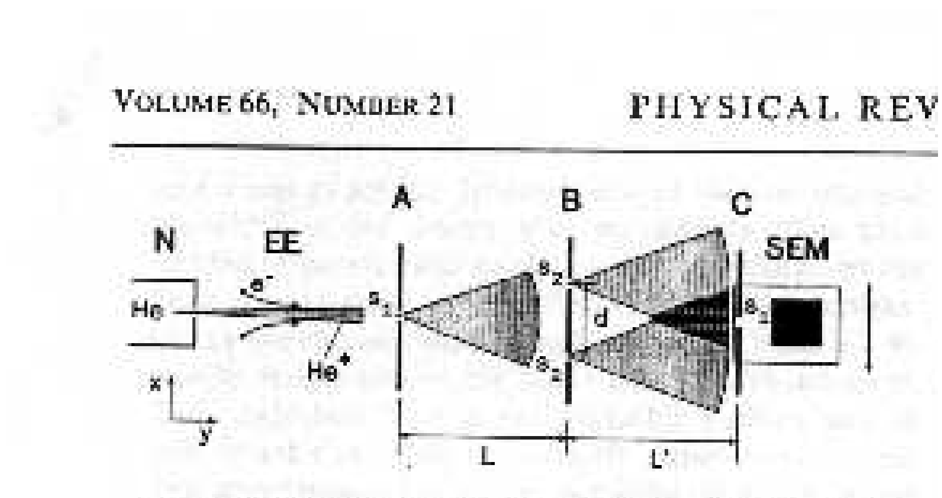


Fibersense Fiber-optic Gyroscope

Atom Interferometry

- Future atom optics-based sensors may outperform existing inertial sensors by a factor of 10^6.
- Current (laboratory) atom optics-based sensors outperform existing sensors by a factor of 10^2.

Young’s double slit with atoms



Young’s 2 slit with Helium atoms

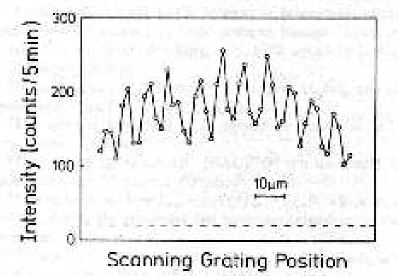


FIG. 5. Atomic density profile, monitored with the 8-μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

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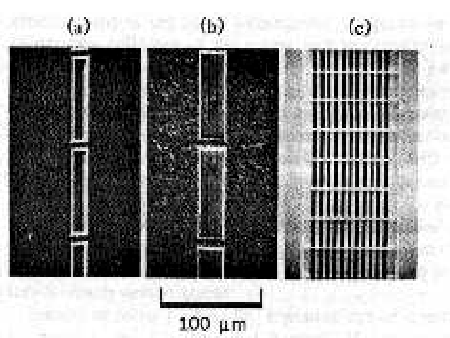
Interference fringes



Slits

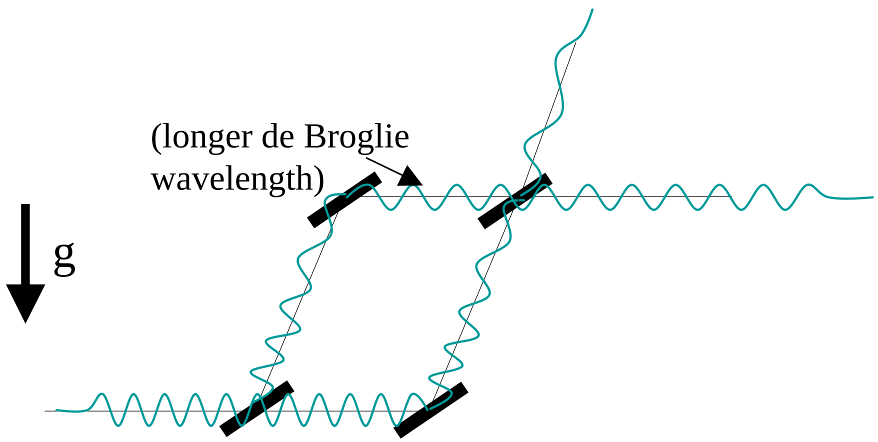
One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991

Atom interferometer force sensors

The quantum mechanical wave-like properties of atoms can be used to sense inertial forces.

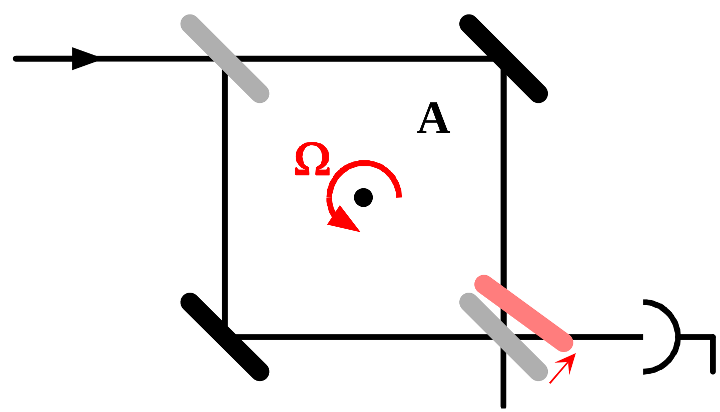
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

Rotations induce path length differences by shifting the positions of beam splitting optics

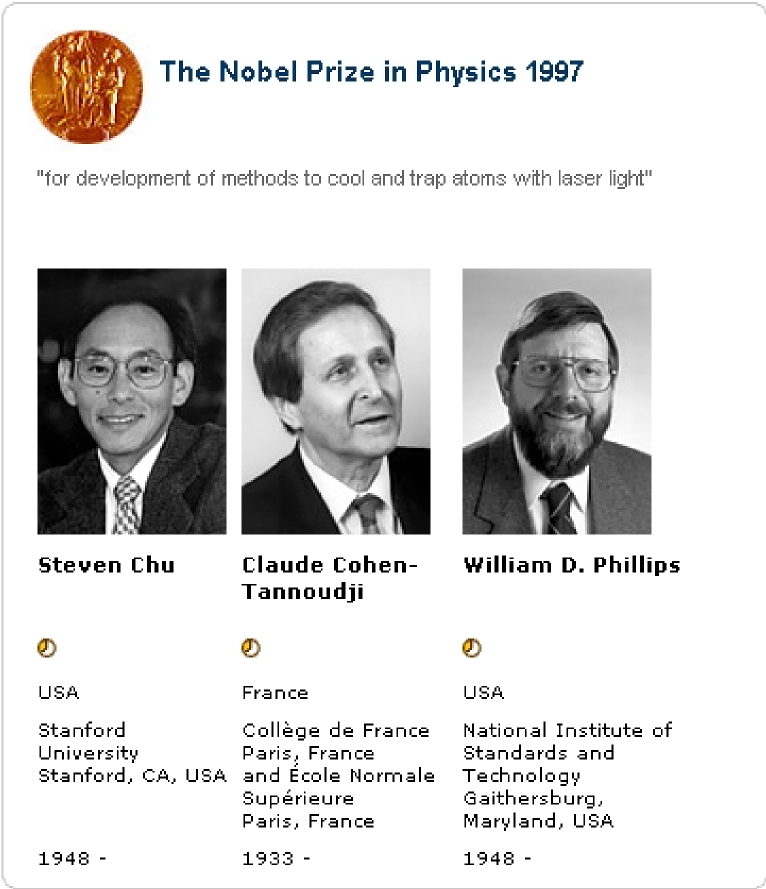


Enabling Science: Laser Cooling

Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

Image source:www.nobel.se/physics

Laser cooling: Laser light is used to cool atomic vapors to temperatures of ~10^{-6} deg K.



Enabling Science: BEC/Atom Lasers

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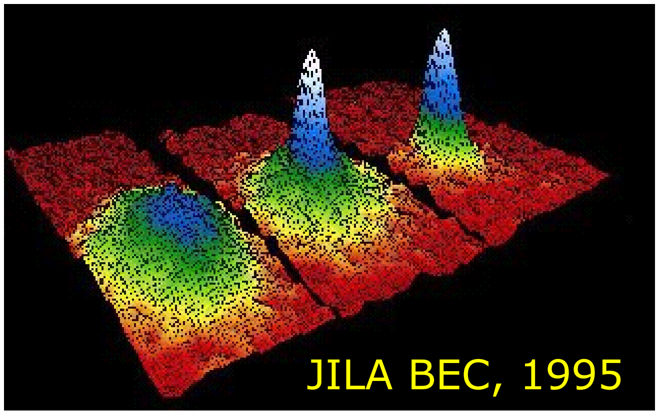
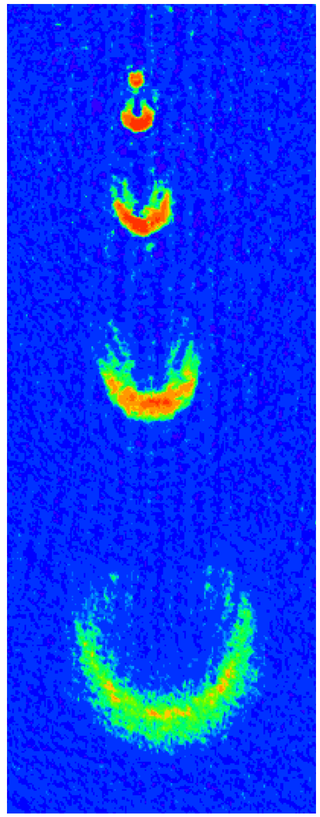
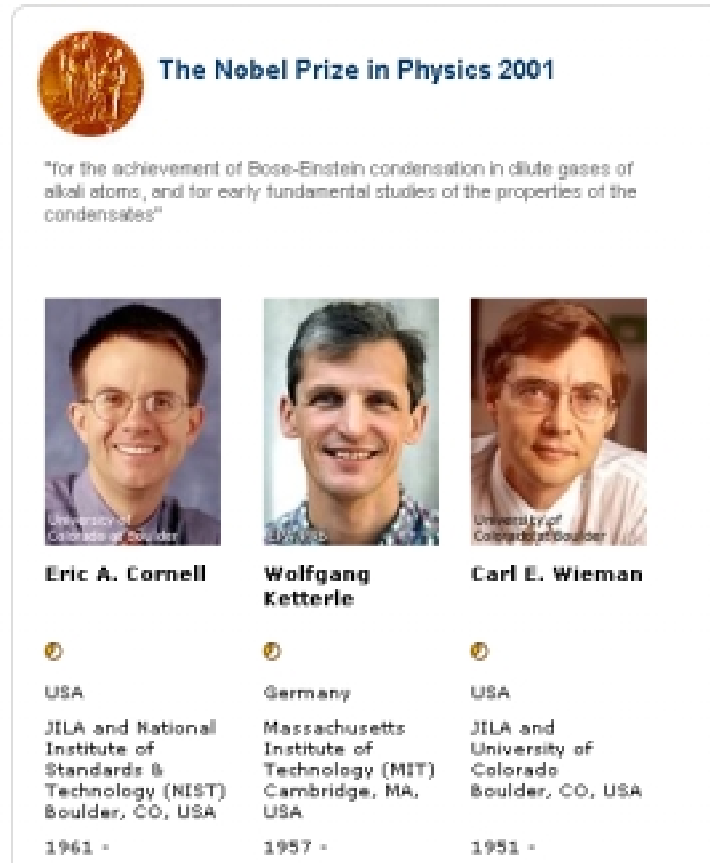


Bose-Einstein Condensation of a dilute Rb atomic vapor



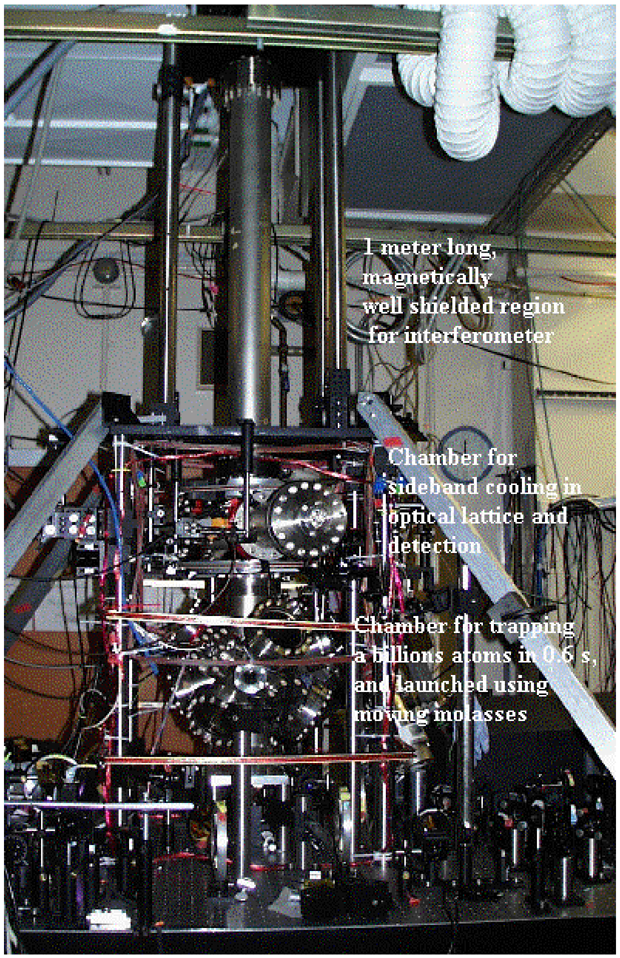
1st Atom Laser, MIT



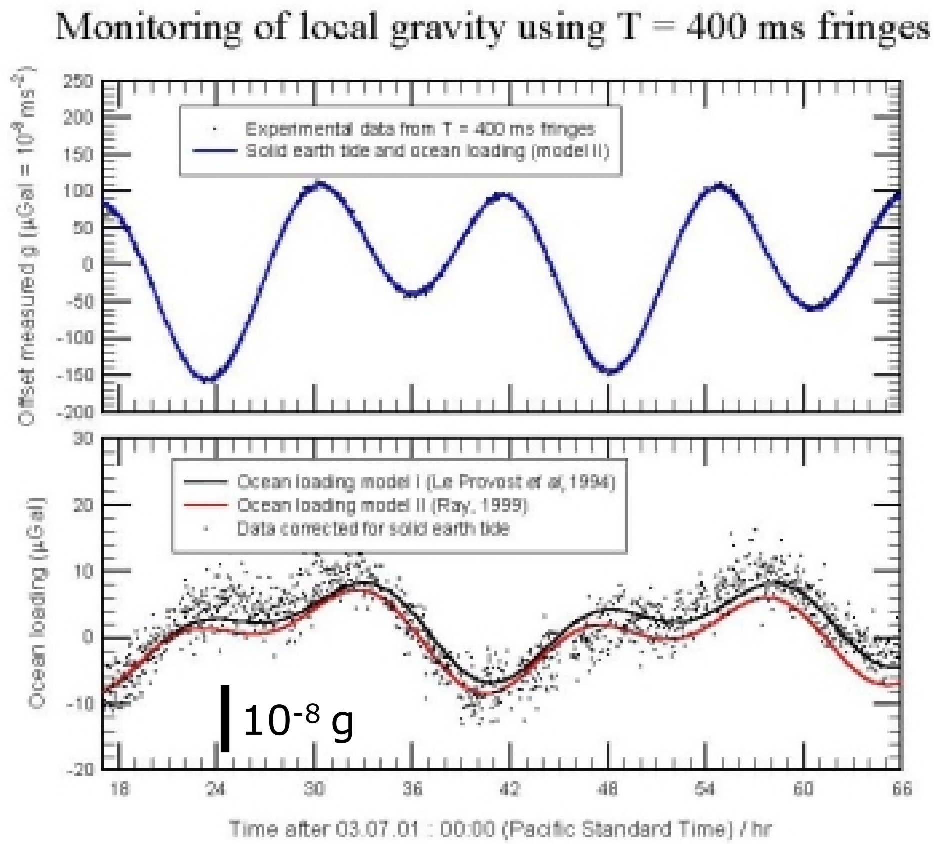
Revolution in production of bright, coherent atomic sources

2001 Nobel Prize!

Stanford laboratory gravimeter



Courtesy of S. Chu, Stanford



Raman sideband cooling used to achieve very long interrogation times (200 nK launch temperature!)

Stanford/Yale laboratory gravity gradiometer

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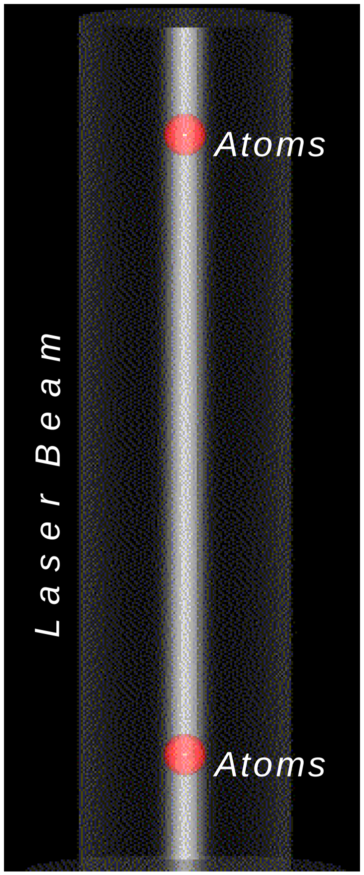

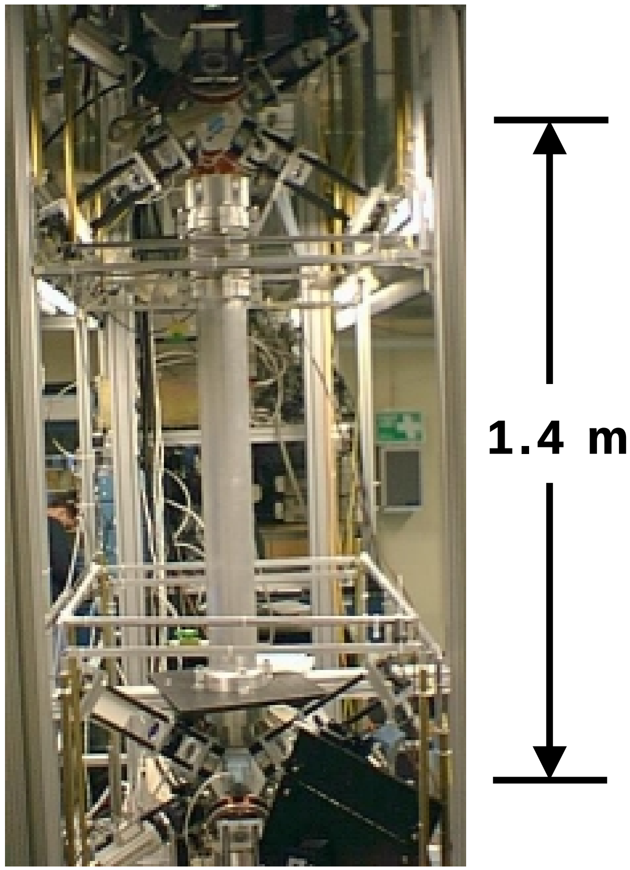

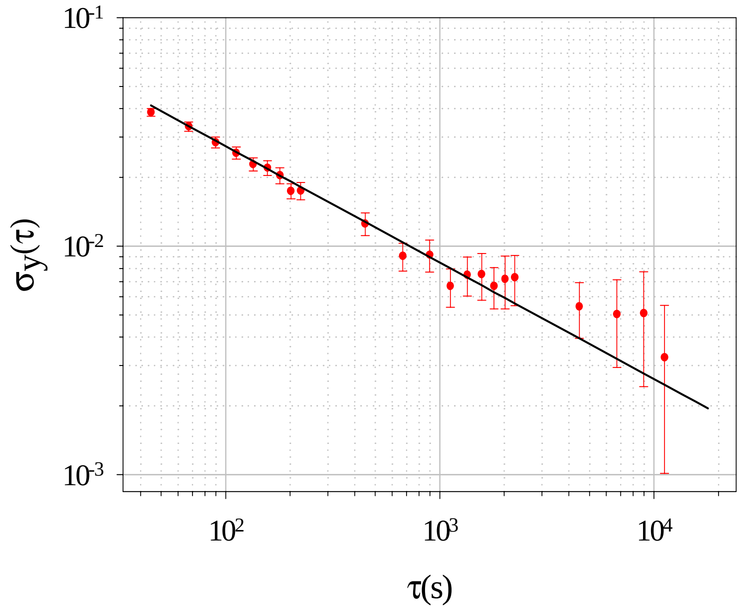

Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

Demonstrated diffential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

Stanford/Yale Gravity Gradiometer: Measurement of G

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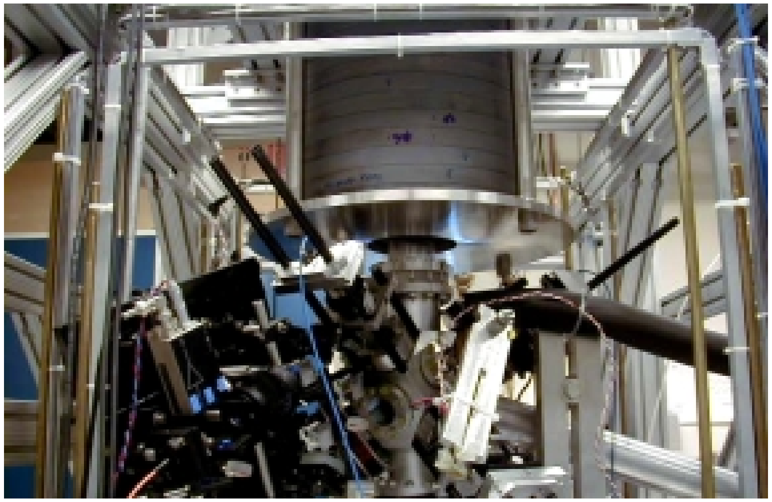
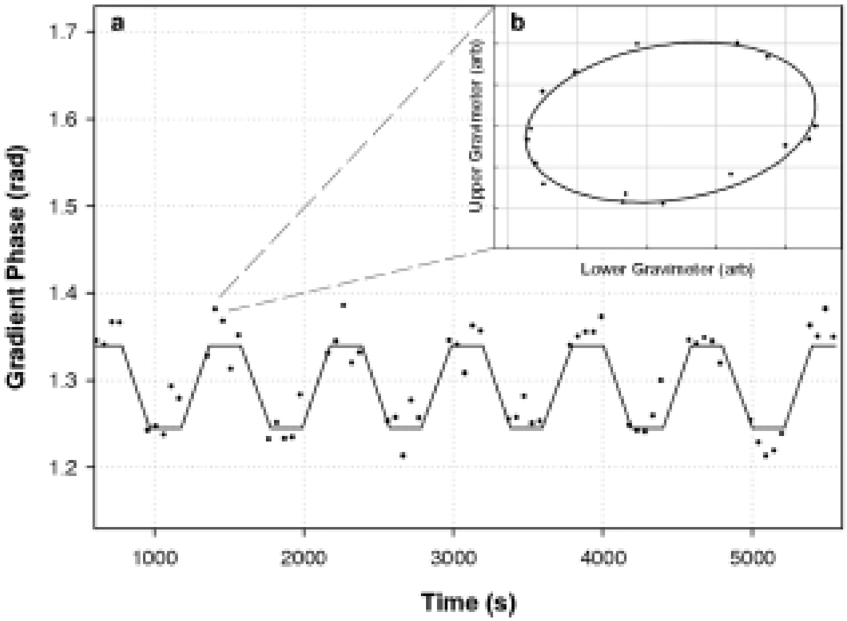


Pb mass translated vertically along gradient measurement axis.



Typical data:

~1x10^{-8} g change in acceleration due to gravitational forces for different Pb positions

Measurement of G

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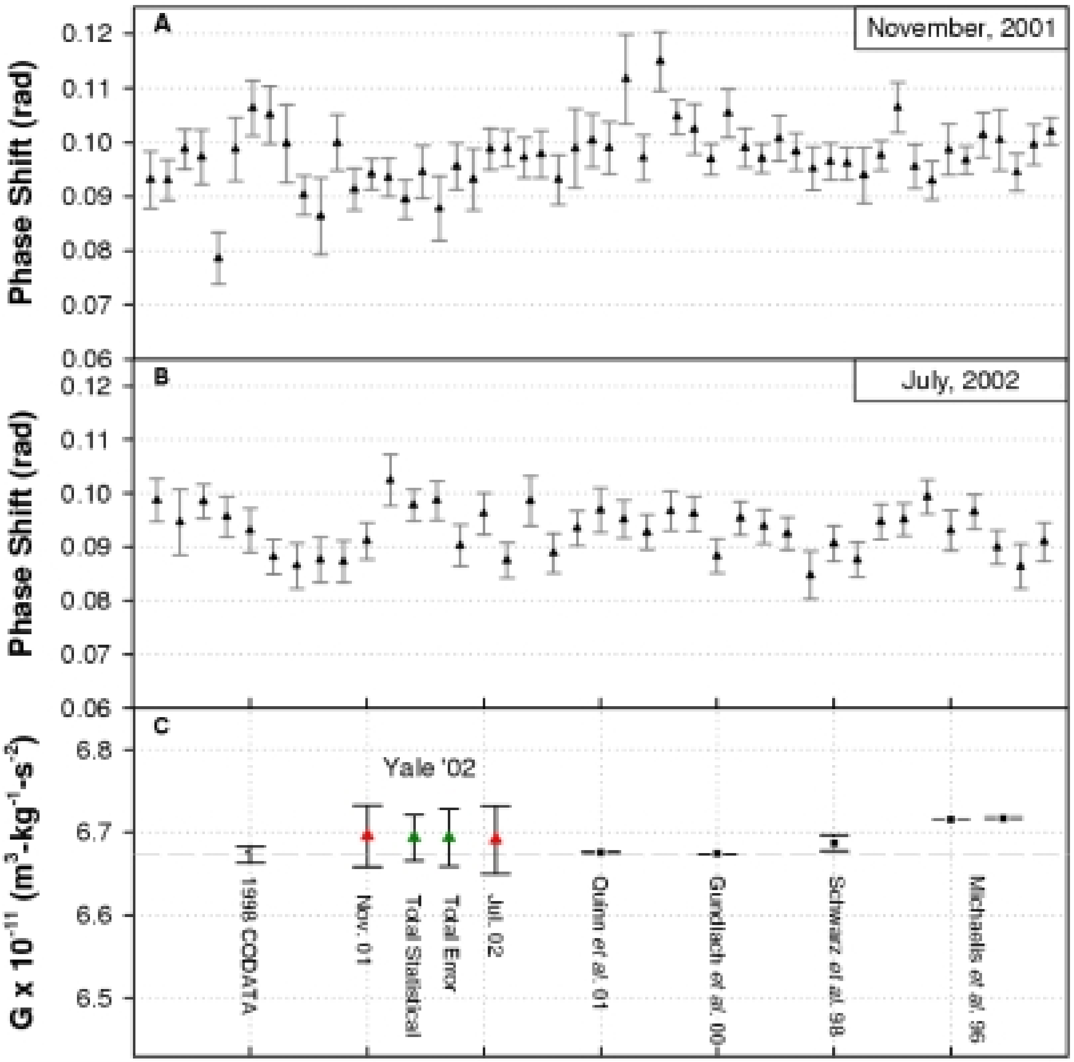


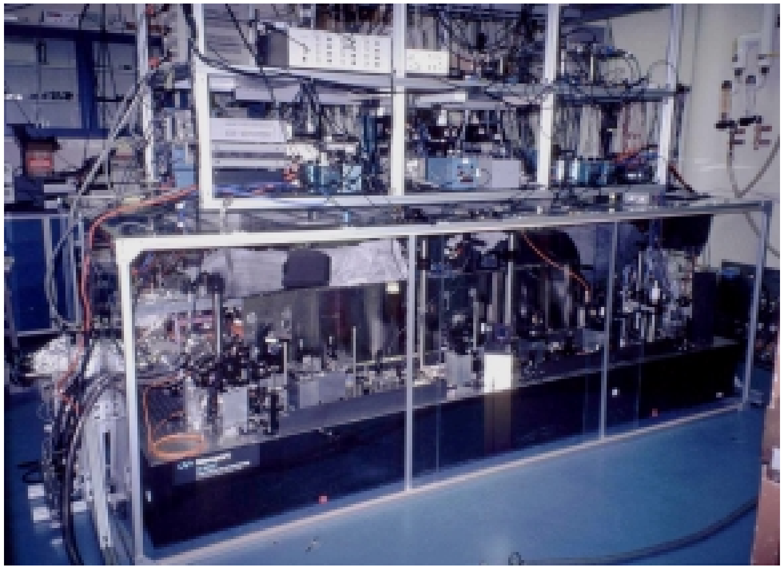
Systematic	$\frac{\delta G}{G}$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

Present sensitivity/accuracy:

$\delta G = 3 \times 10^{-3}$ G

Measurement consistent with accepted value

Stanford/Yale laboratory gyroscope

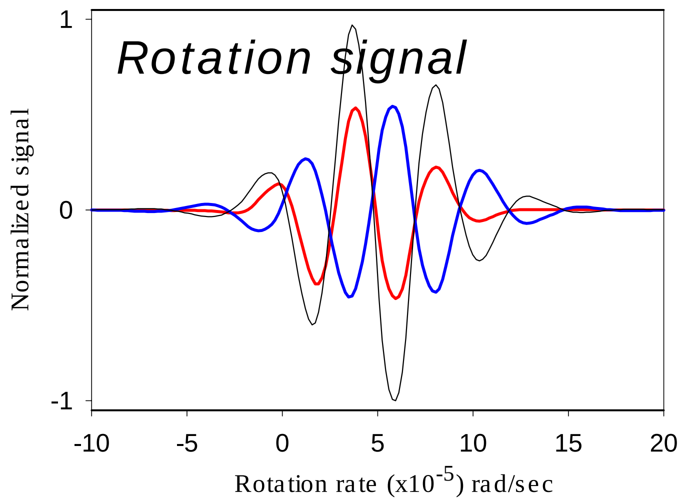


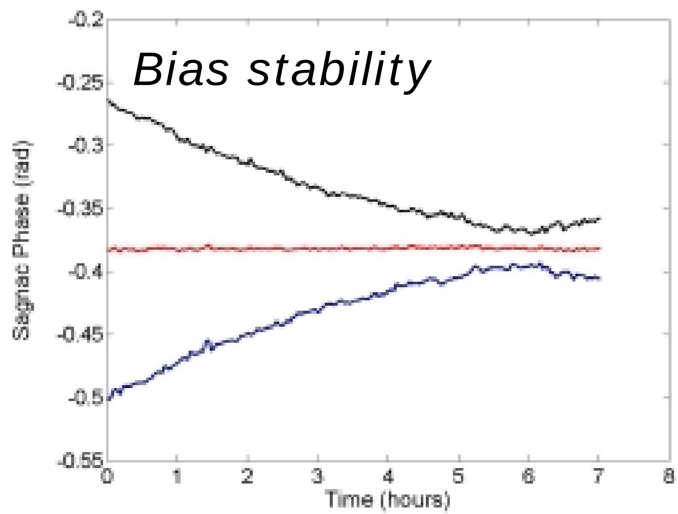
AI gyroscope, demonstrated laboratory performance:

2×10^{-6} deg/hr$^{1/2}$ ARW

< 10^{-4} deg/hr bias stability

Compact, fieldable (navigation) and dedicated very high-sensitivity (Earth rotation dynamics, tests of GR) geometries possible.





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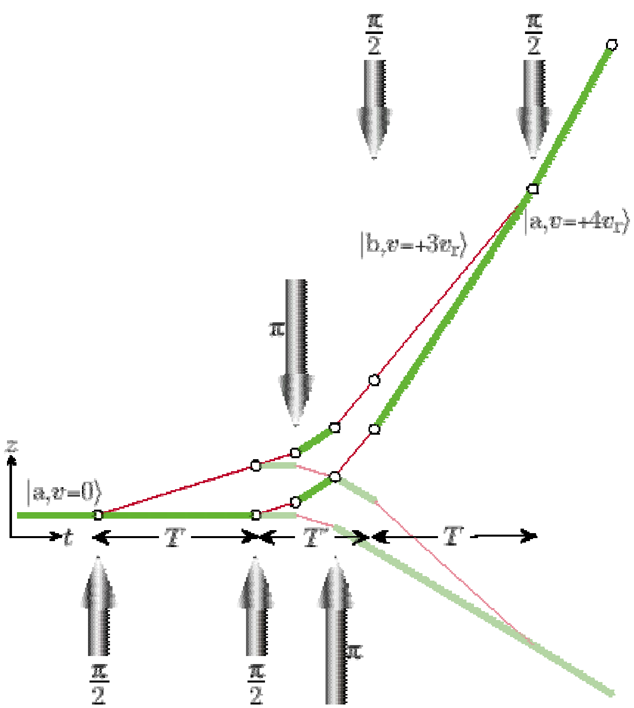
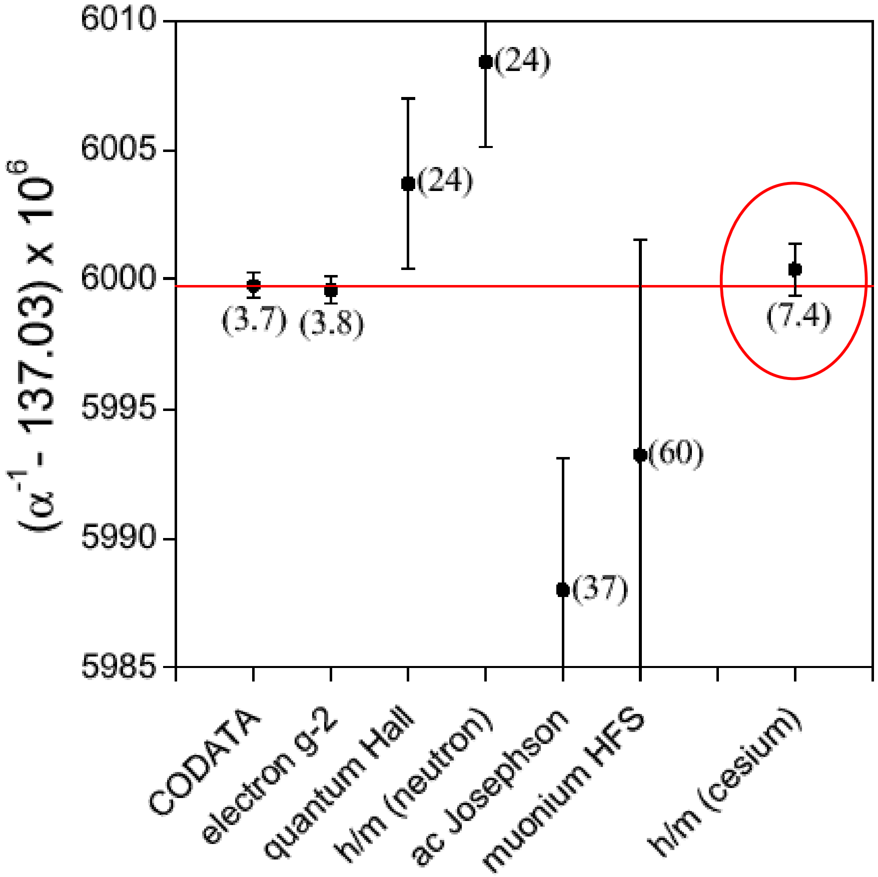
Stanford h/m





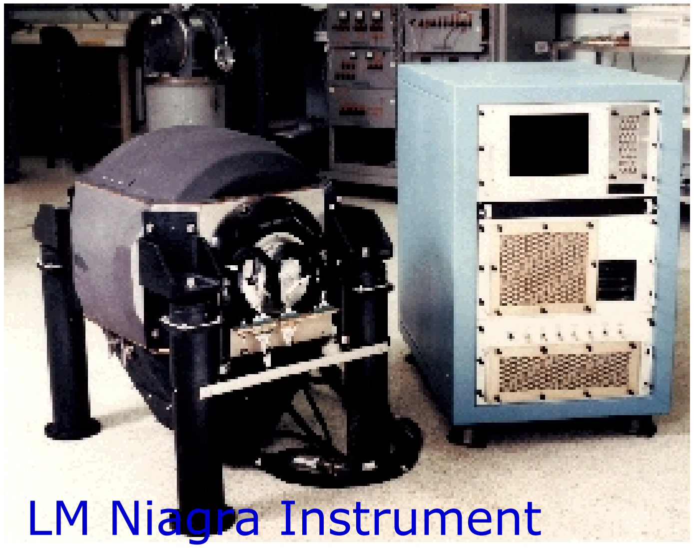
Courtesy of S. Chu, Stanford (talk by A. Wicht, Wednesday)

Science and Technology Applications

Airborne GG validation: BHP FALCON program

Existing technology

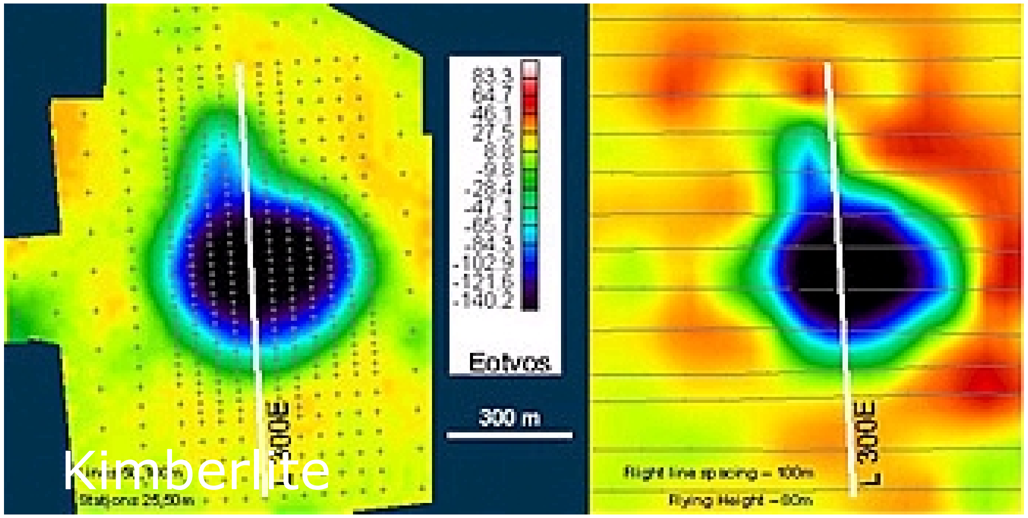
Sanders Geophysics



LM Niagra Instrument

Land: 3 wks.

Air: 3 min.



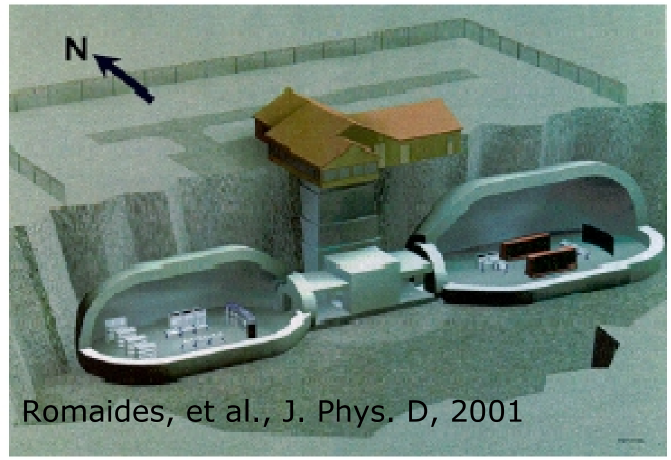
Kimberlite

AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

Underground structure detection

Gravity gradiometers can detect underground structures via their gravitational signatures.

AI appears to be sole sensor technology capable of meeting stringent sensitivity and accuracy requirements.

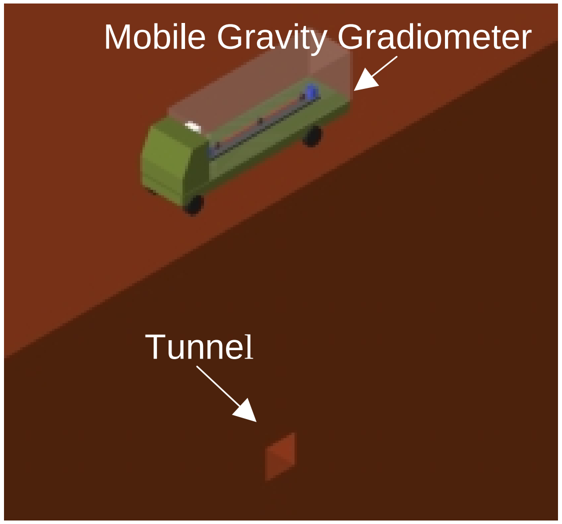


Romaides, et al., J. Phys. D, 2001

Strategic moving platforms for gravity gradiometry:

- Helicopter/UAV platform
- Satellite reconnaisance (?)
- Truck

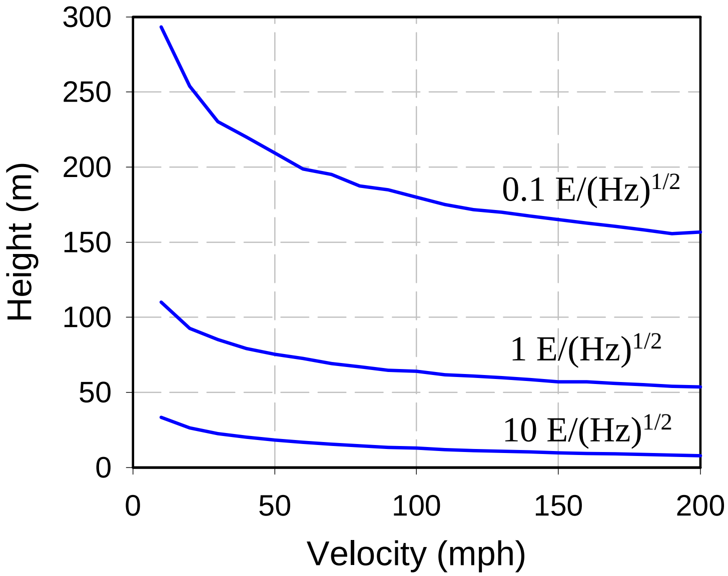
Tunnel detection



Tunnel model:

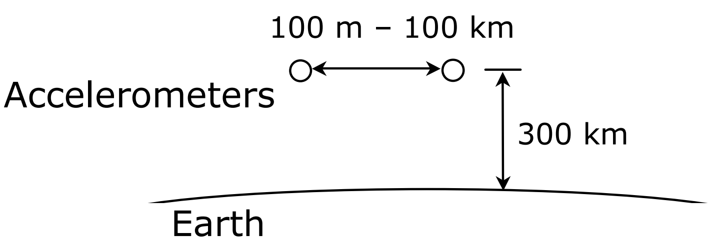
5 m x 5 m tunnel

$\delta\rho$ = 3 g/cm^3



Field-ready 1 E/Hz$^{1/2}$ instrument currently under development for truck/helicopter/aircraft platform

Geodesy



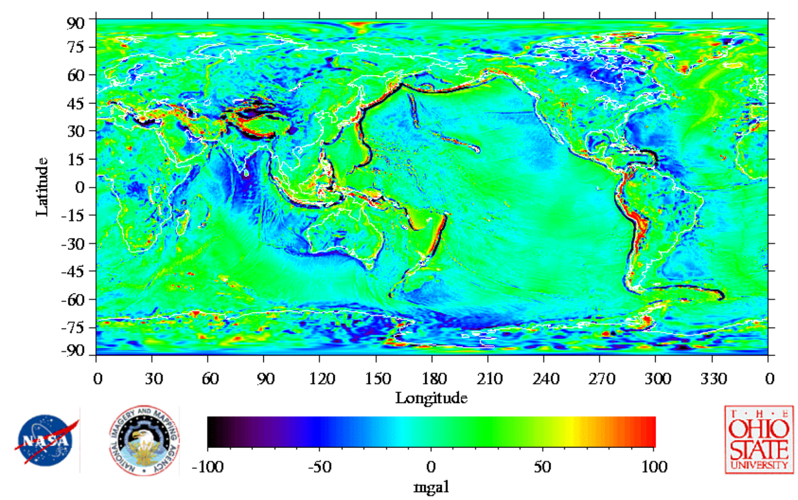
Accelerometer sensitivity: 10^{-13} g/Hz$^{1/2}$
- Long free-fall times in orbit

Measurement baseline
- 100 m (ISS)
- 100 km (Satellite constellation)

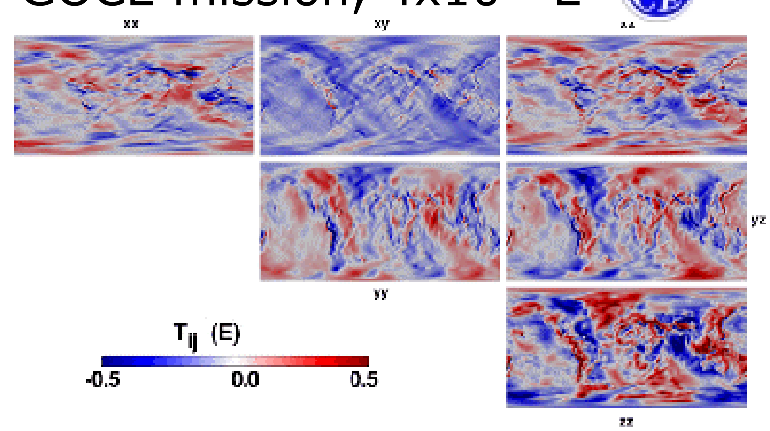
Sensitivity:
- 10^{-4} E/Hz$^{1/2}$ (ISS)
- 10^{-7} E/Hz$^{1/2}$ (Satellite constellation)

Earthquake; water table monitoring (collaboration with T. Parsons, USGS)

30' Mean Gravity Anomalies: EGM96 (Nmax=360)



GOCE mission, 4×10^{-3} E



http://www.esa.int/export/esaLP/goce.html

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Test of General Relativity

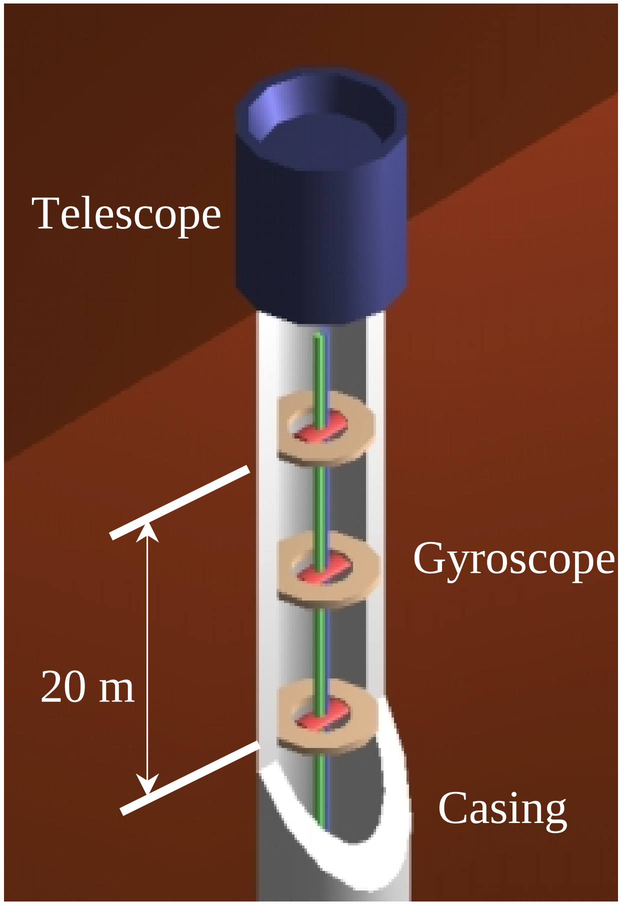
Lorentz-like force law:

$$\frac{d\vec{v}}{dt} = \vec{g} + \frac{\vec{v}}{c} \times \vec{H}$$

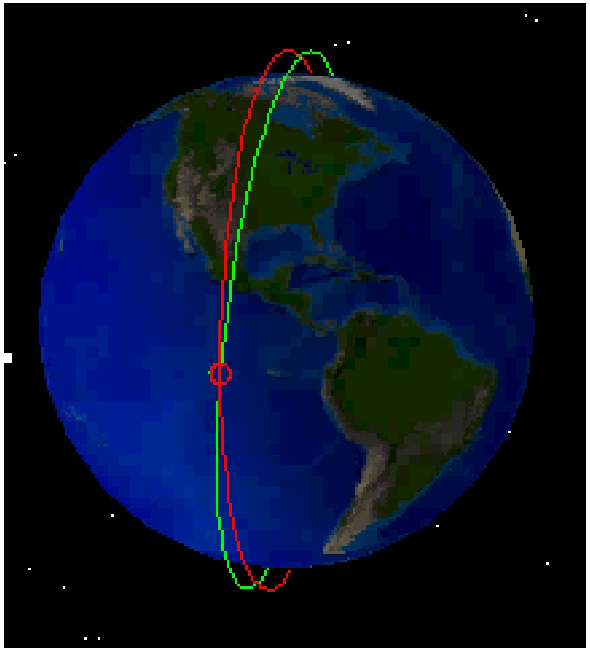
$$\vec{H} = \frac{2G}{c}\left[\vec{S} - \frac{\vec{S}\cdot\hat{r}}{r^3}\hat{r}\right]$$

S is angular momentum of rotating body

Basic idea: Compare rotation inferred from astrophysical observations to atom interferometer gyro signal.



Ground-based



Satellite-based

10^{-14} rad/sec rotation sensitivity required

Equivalence Principle

Compare relative acceleration of Cs and Rb atoms (or two Rb isotopes) using AI methods.

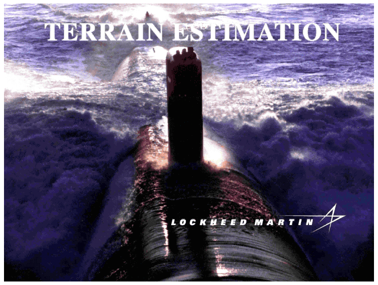
Constrain possible "new physics" beyond Standard Model at unprecedented levels.

10^{-13} g/Hz$^{1/2}$ differential acceleration sensitivity appears feasible on ISS/free-flyer (in collaboration with L. Maleki, JPL through NASA Fund. Phys./flight definition)

RECENT theory: "Little String Theory at a TeV", I. Antoniadis, S. Dimopoulos, A. Giveon, hep-th/0103033, 2002.

Dimopoulos: "More speculative than extra-dimensions...."

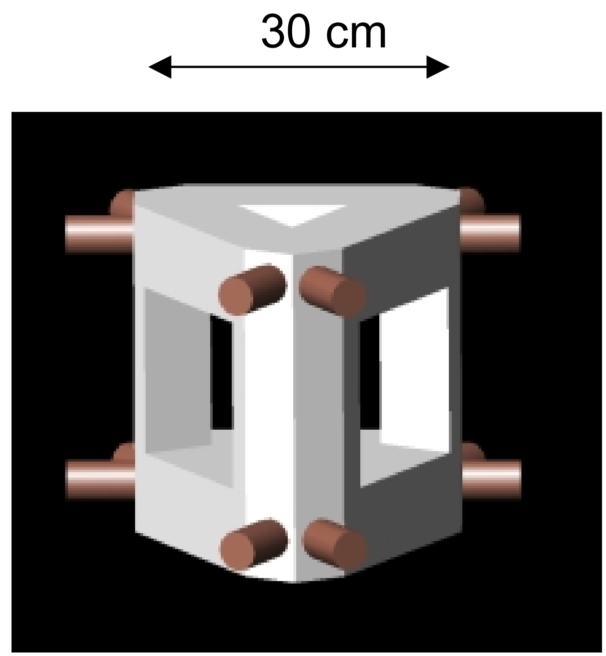
Navigation



High-accuracy IMU with gravity compensation under development for Trident submarine navigation.

Array of 3-axis accelerometers on rigid platform

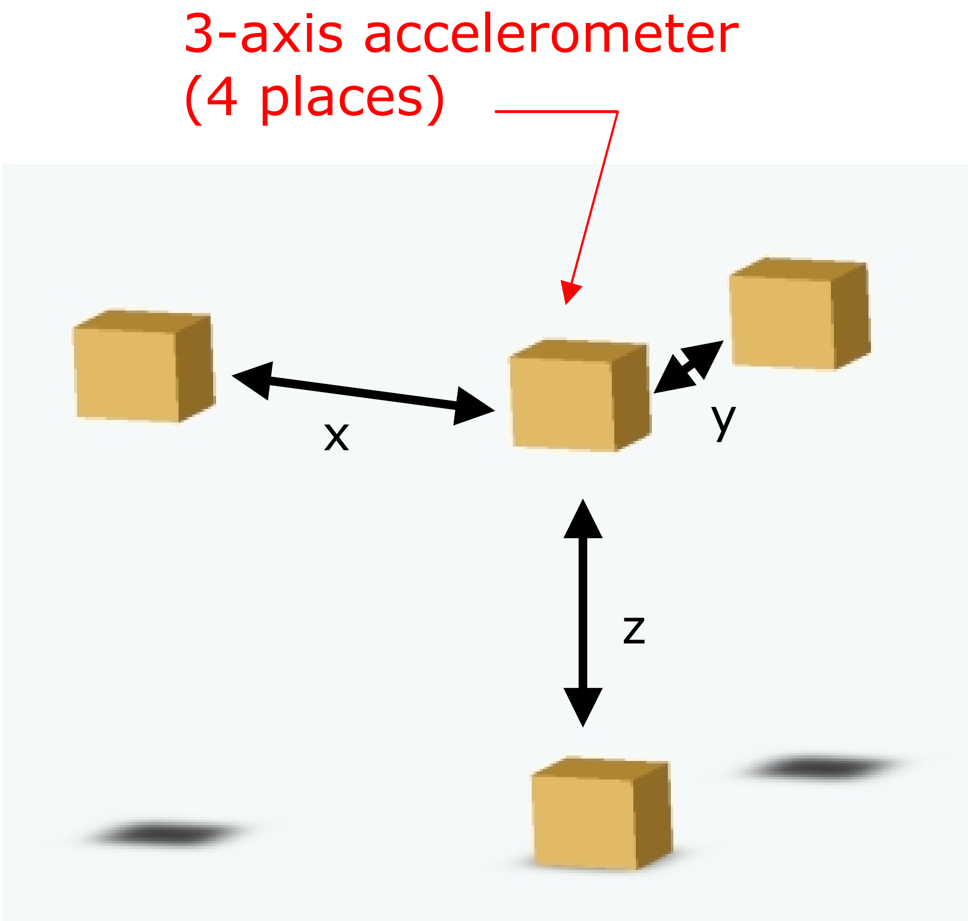
- In-line differential acceleration measurements along independent axes allow discrimination of angular accelerations from gravity gradients
- Integrate angular acceleration to correct for centrigual perturbations



2nd generation proof-of-concept instrument. Brown = laser beams; Grey = vacuum cell

Long-term vision: low-cost, high-reliability gravity compensated IMU's.

Navigation with accelerometer arrays



Allows for gravity anomaly and platform position determination.

High accuracy gyroscopes may not be needed.

Differential acceleration measurements

Differential acceleration measurements contains terms due to rotations and angular accelerations:

$$\begin{pmatrix} f_{1x} - f_{0x} \\ f_{1y} - f_{0y} \\ f_{1z} - f_{0z} \end{pmatrix} = \begin{bmatrix} -\left(\Gamma_{xx} + \Omega_y^2 + \Omega_z^2\right) & -\dot{\Omega}_z - \left(\Gamma_{xy} - \Omega_x\Omega_y\right) & \dot{\Omega}_y - \left(\Gamma_{xz} - \Omega_x\Omega_z\right) \\ \dot{\Omega}_z - \left(\Gamma_{xy} - \Omega_x\Omega_y\right) & -\left(\Gamma_{yy} + \Omega_x^2 + \Omega_z^2\right) & -\dot{\Omega}_x - \left(\Gamma_{yz} - \Omega_y\Omega_z\right) \\ -\dot{\Omega}_y - \left(\Gamma_{xz} - \Omega_x\Omega_z\right) & \dot{\Omega}_x - \left(\Gamma_{yz} - \Omega_y\Omega_z\right) & -\left(\Gamma_{zz} + \Omega_x^2 + \Omega_y^2\right) \end{bmatrix} \begin{pmatrix} \rho_x \\ \rho_y \\ \rho_z \end{pmatrix}$$

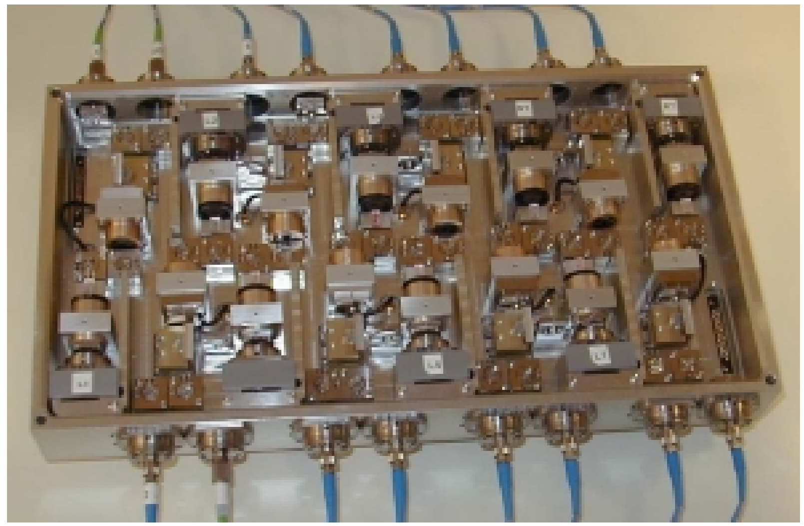
Γ_{ij}: Gravity gradient
Ω_i: Rotation
ρ_i : Displacement

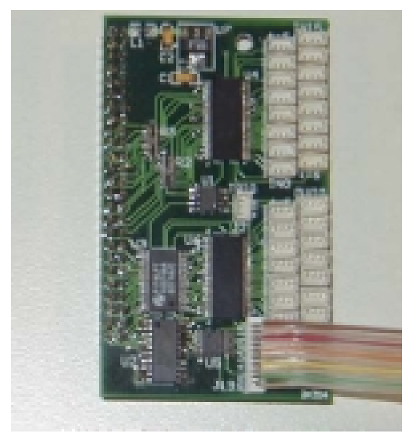
Accelerometer arrays enable high-accuracy navigation.

See PLANS 2002, A. Zorn, Dynamics Research Corporation

Compact prototype under development

6dof motion testing platform

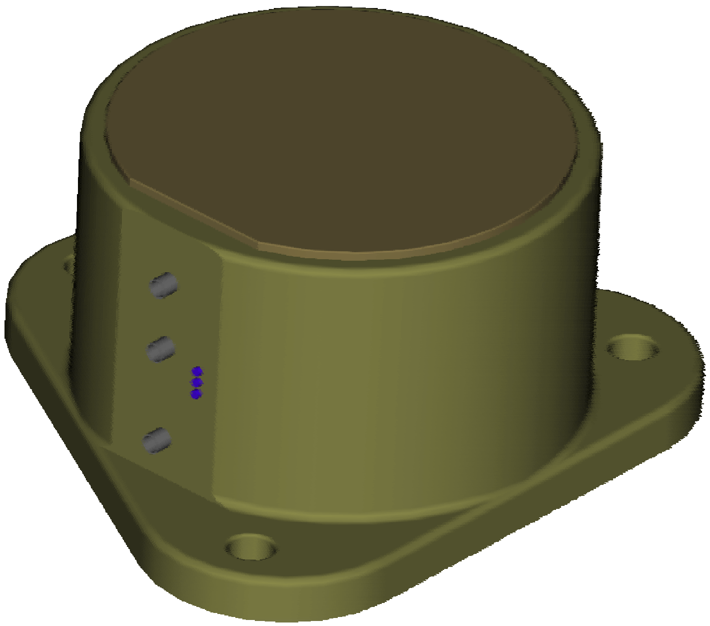




Component sub-systems under development

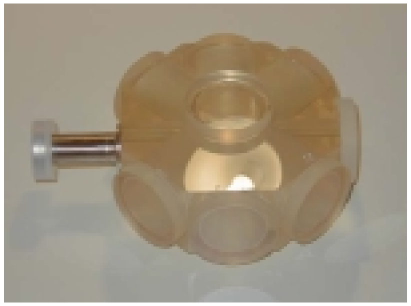
Field-ready prototype available FY03, est.

Ground-based accelerometer



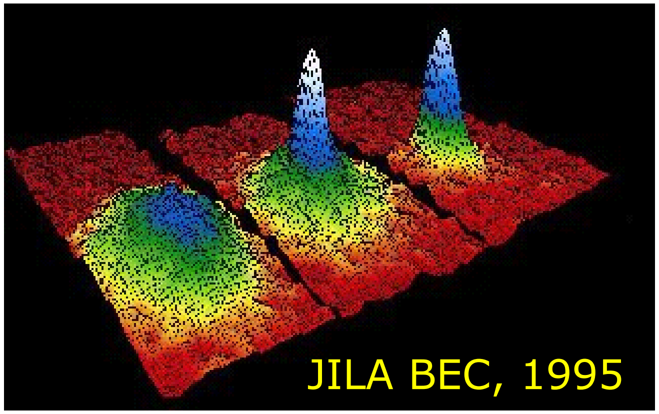
Under development:

2.75”x1.75”, 10^{-8} g/Hz$^{1/2}$
2-axis accelerometer

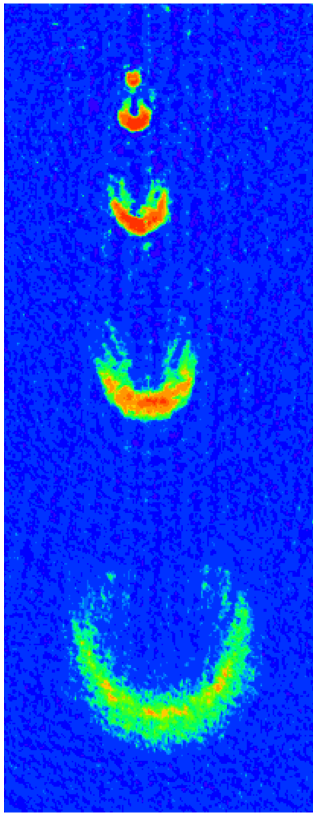


BEC impact

Atom lasers



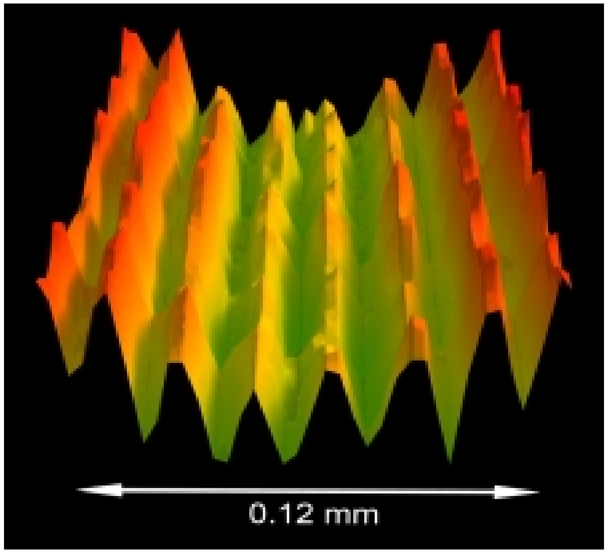
Bose-Einstein Condensation of a dilute Rb atomic vapor



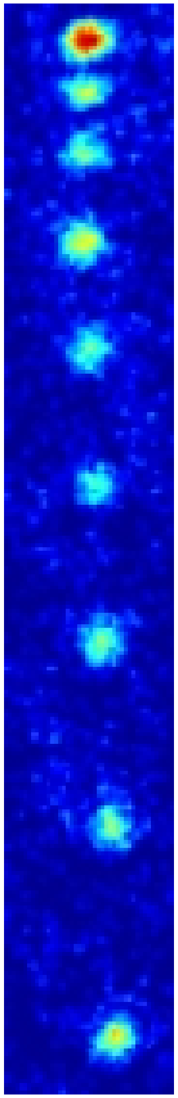
1st Atom Laser, MIT

Revolution in production of bright, coherent atomic sources

Atom interferometry with atom lasers



Interference of two overlapping Bose-Einstein condensates: demonstrates analogy with laser light sources (Ketterle, MIT)



Measurement of g with a mode-locked atom laser (Yale)

Proof of principle with potential for 1000 x improvement in gravimeter sensitivity.

Pulse output frequency is proportional to g.

Demonstration of coherence properties and possible applications

Next generation atom-optic devices

	Atomic Source	Atom Optics	Read-out
Current Generation	• Laser cooled atoms	• Photon recoil • Free-space diffraction grating	• Shot-noise limited
Next Generation	• Atom lasers	• Waveguides	• Quantum correlated state (1/N)

Next generation pay-off: compact, ultra-sensitive accelerometer, gyroscopes, clocks

Possible 1000x performance gain in next generation sensors

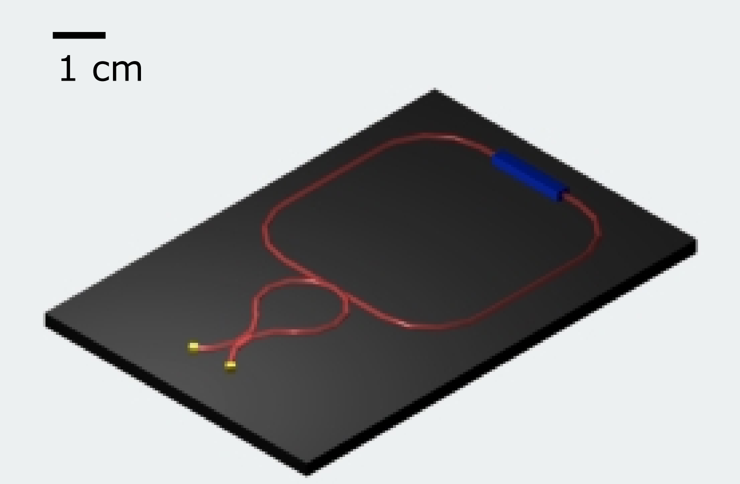
Waveguide AI sensor types

Waveguide devices:

Unproven (coherence has yet to be demonstrated!)

Likely very high sensitivity, intermediate accuracy.

Gyroscope, gravity gradient, and accelerometer topologies exist.

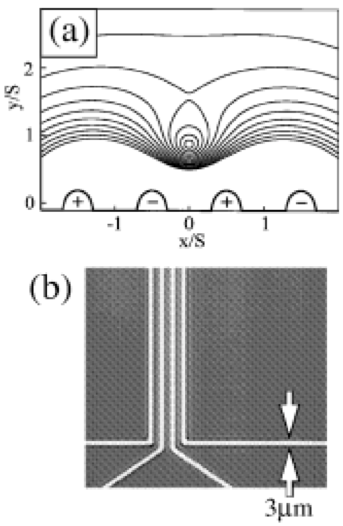


Atom Laser Gyroscope

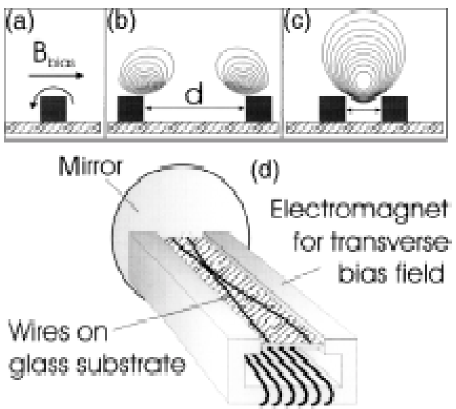
Technology vision:
Compact, ultra-sensitive (1000x existing sensors), inexpensive sensors

Atom Waveguides

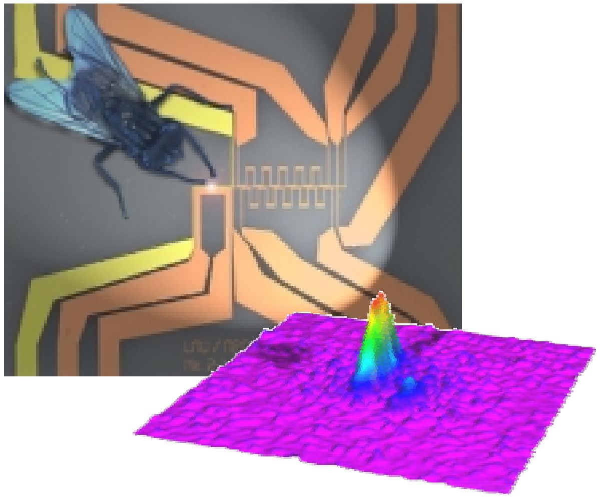
Basic atom guiding concepts have been demonstrated by several groups.



Prentiss, Harvard



Anderson, JILA

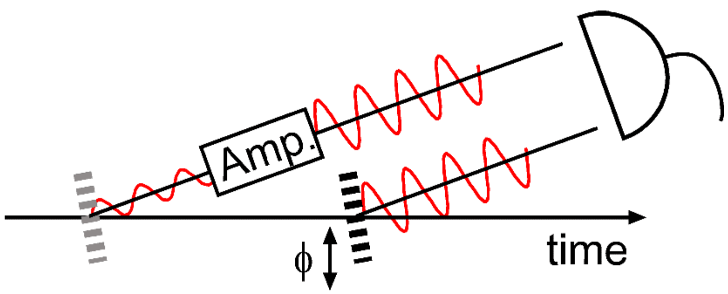


MPQ, Garching

Achieved Bose-Einstein condensation in microtrap.

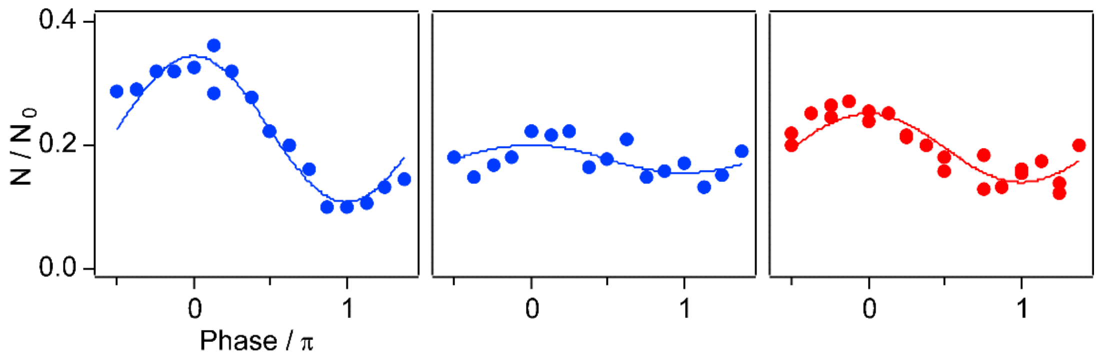
Matter-wave amplification

Experiment



Ketterle, MIT

Results



Interference of an (unamplified) seed pulse with a reference pulse of equal intensity.

A weaker seed pulse led to a reduced fringe contrast.

When the weak seed pulse was amplified, an increase of the fringe contrast provided the proof for the phase-coherence of the atom amplification process

Laboratory demonstration of coherent matter-wave amplification

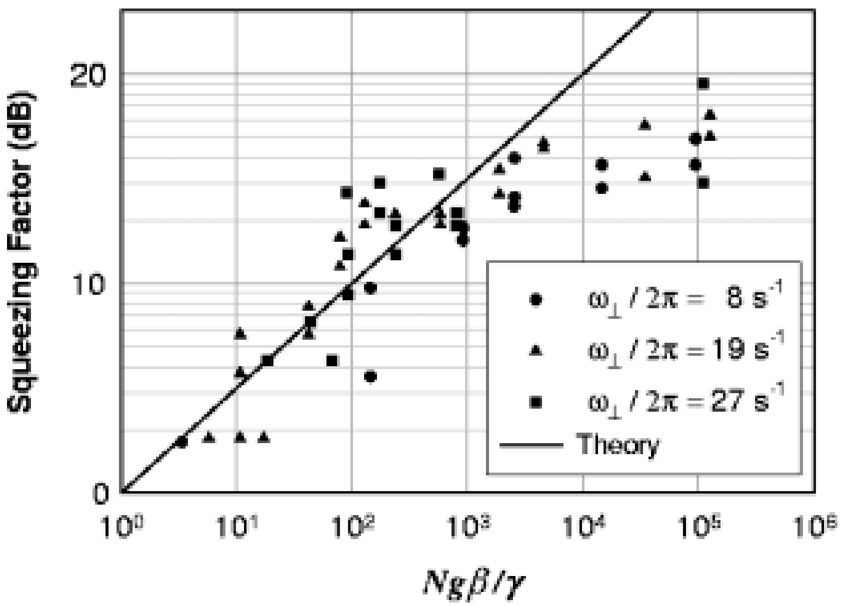
Atom interferometry with squeezed state atom lasers

Quantum mechanics of many-particle systems allows for measurement sensitivities below the standard (classical) shot-noise limit.

Atom interferometry with squeezed states.

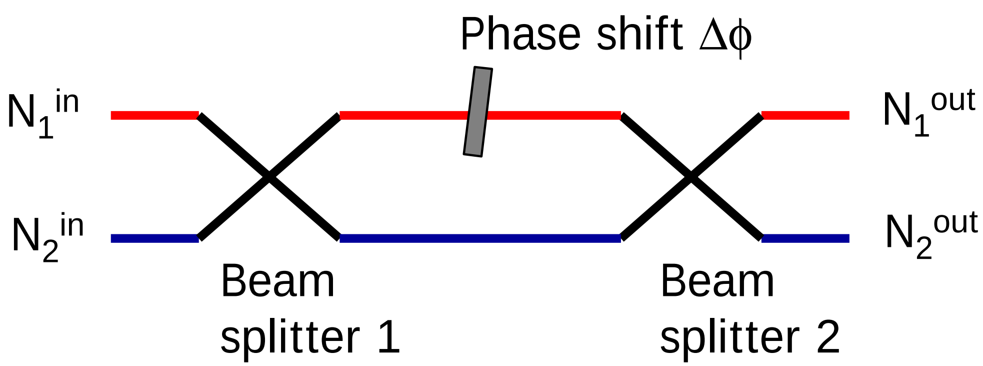
Possible 1000-fold improvement in sensor sensitivity.

Laboratory demonstration of squeezed-state formation



Heisenberg interferometry with degenerate Bose gases

Sub shot-noise interferometry with squeezed/Fock states:
(following Holland and Burnett, 1993)



Dual Fock state at input ports

Number measurements at output ports

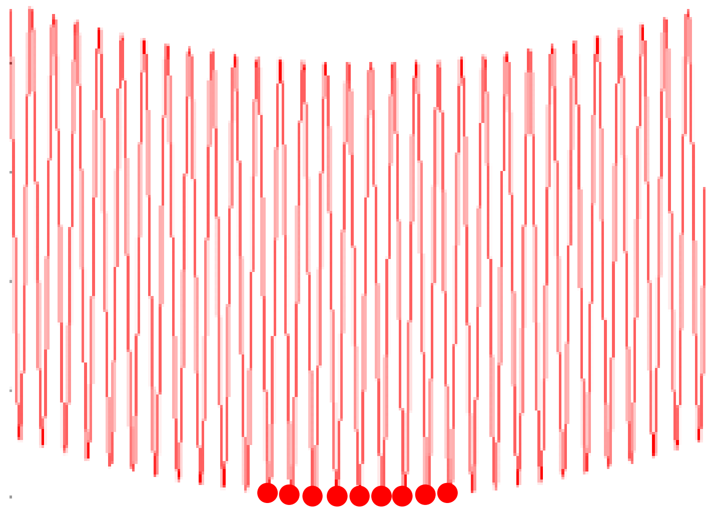
Capable of resolving phase shifts at Heisenberg limit ($\Delta\phi \sim 1/N$).

Possible significant gains for interferometer sensitivity

Bouyer and Kasevich, PRA, 1996 (for BEC atoms)

Correlated atom systems

BEC in lattice potentials



Our regime:

- 1-D
- 100's of atoms per site, 10's of lattice sites
- Weak tunneling (0.01 – 300 Hz, tunable)
- Strong interactions (100 – 500 Hz mean field per particle)

Why interesting?

- Quantum states highly correlated/entangled
- Growing links with CM Theory/QPT
- Possible applications to precision measurement/quantum information

This talk

- Ground state properties
- Dynamic response
  - In-situ transport measurements

Bose-Hubbard Hamiltonian

$$H = \gamma \sum_{<i,j>} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} g \beta_i \sum_i \hat{a}_i^\dagger \hat{a}_i^\dagger \hat{a}_i \hat{a}_i - \sum_i \mu_i \hat{a}_i^\dagger \hat{a}_i$$

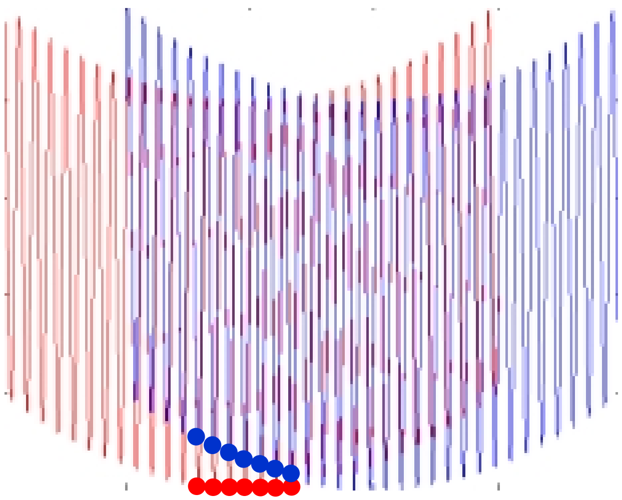
tunneling mean-field external potential

Solve for ground-state and dynamics for ~3000 atoms occupying 16 lattice sites in harmonic potential.

Problem: Hilbert space is huge. Approximations required.

Transport measurement: Center-of-mass oscillation

CAMOS
Nov. 2002



Suddenly displace harmonic potential, leaving corrugated potential fixed.

Observe subsequent dynamic evolution of array center-of-mass (oscillation amplitude and frequency).

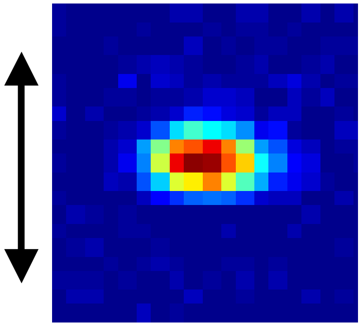
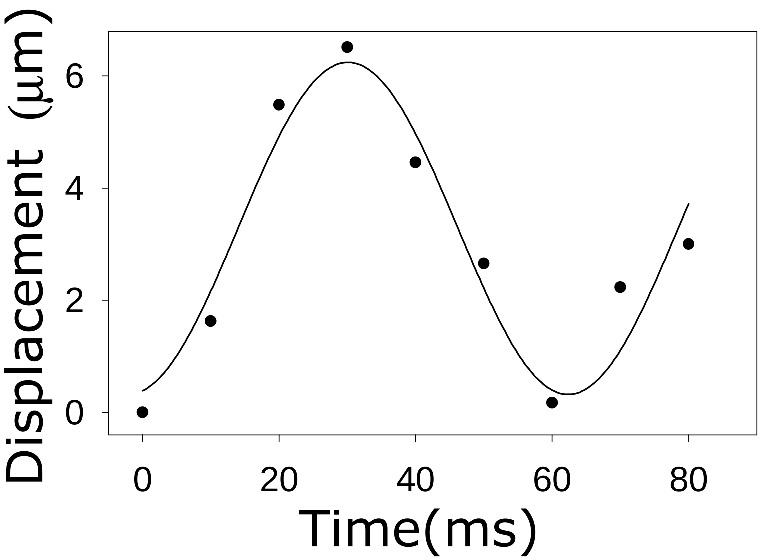


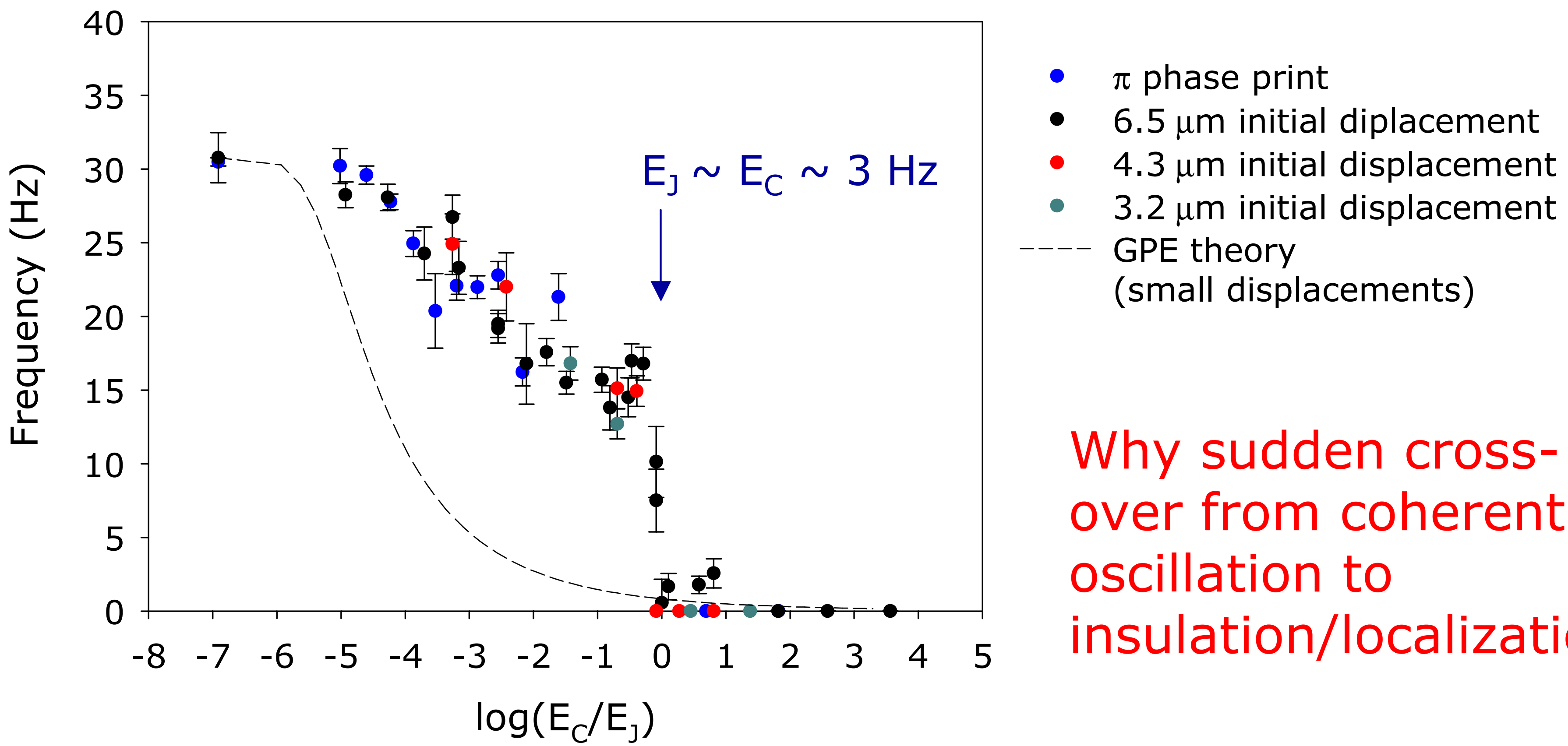
Image of lattice array.

~150 atoms in central well.



Quantum insulating cross-over

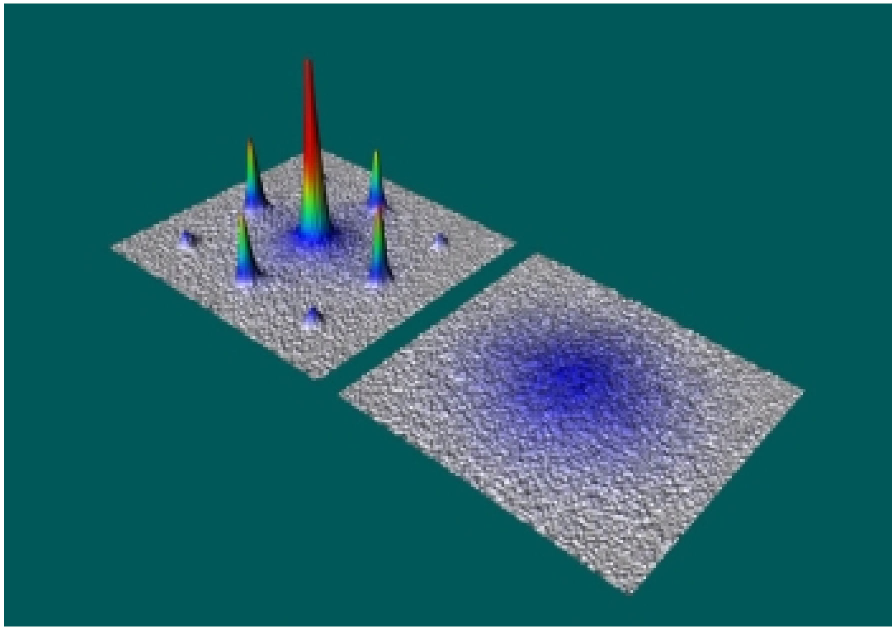
$E_J \equiv N\gamma = $ (# atoms)(tunneling freq.)
$E_C \equiv g\beta = $ (mean field energy per atom)



Why sudden cross-over from coherent oscillation to insulation/localization?

Related work from MPQ

MI transition in 3D optical lattice. Approximately 3 atoms per lattice site.



I. Bloch, Nature, 2002.

Future

- Quantum critical region
  - Quantum phase transitions
- Rotating lattice sites
  - Analog to fractional quantum Hall
- Fermions in lattice
  - High Tc analog
- QIS
  - Physics-based (use atoms in lattice to understand CM systems)
  - New algorithms for factorization